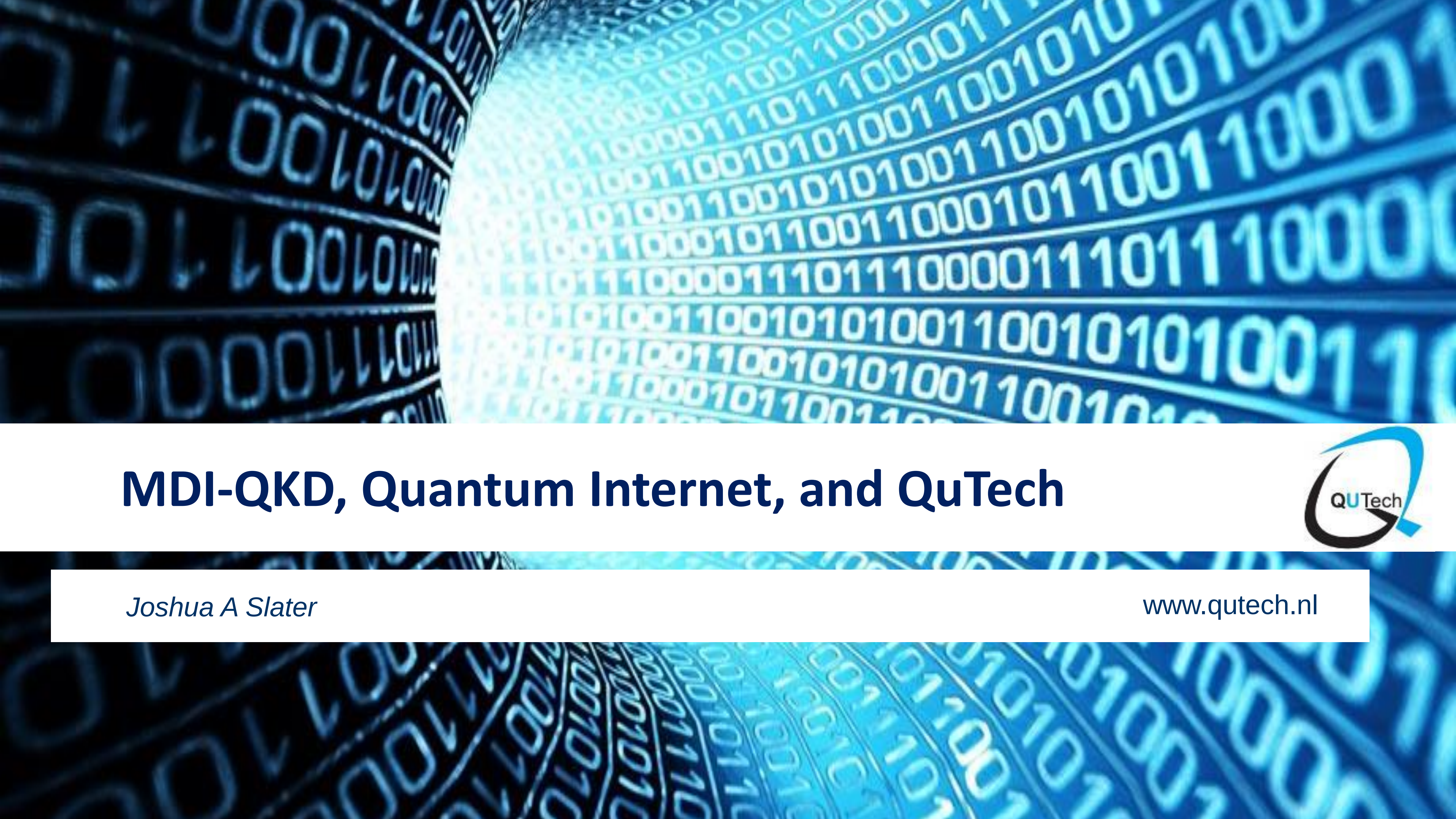


MDI-QKD, Quantum Internet, and QuTech

Joshua A Slater

www.qutech.nl

Quantum Internet

A Communication Network Exploiting the Quantum Properties of Light

I have an important document and I want to authenticate it

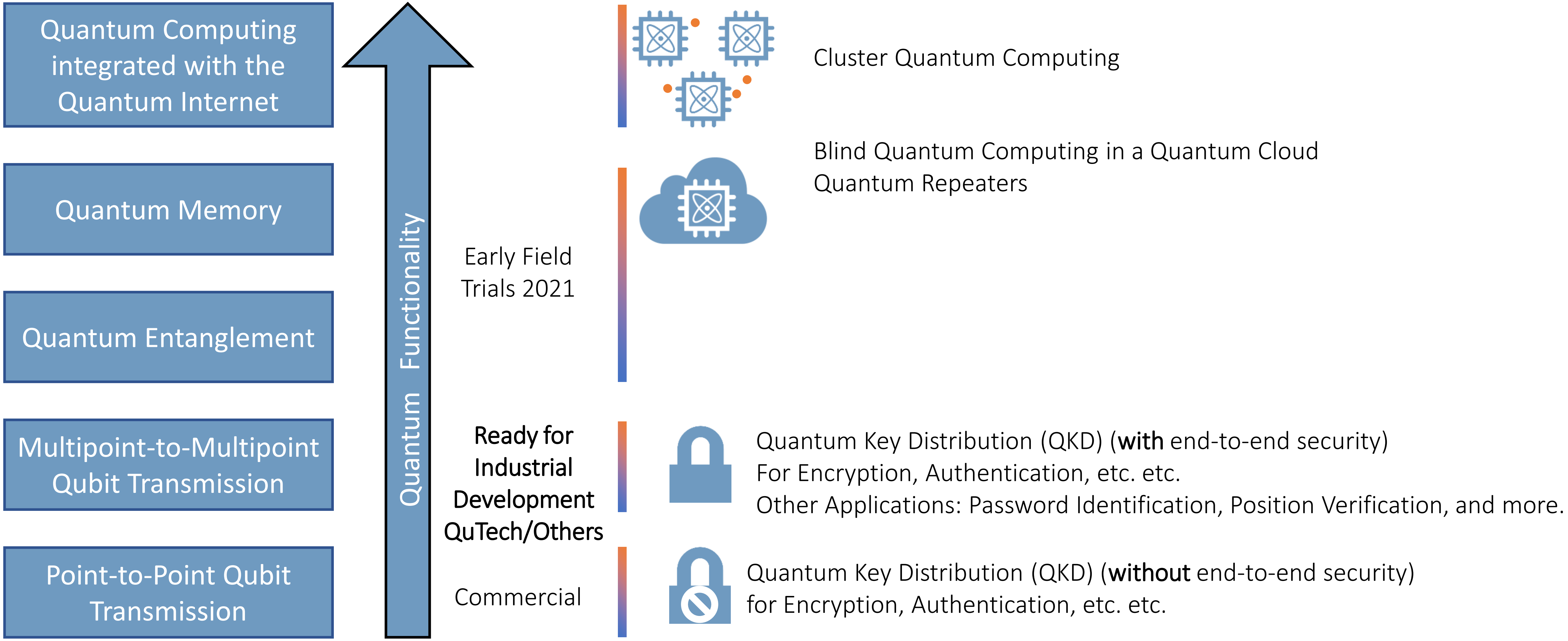
I’m very important. I want to encrypt an entire message

I’m a Quantum Computer, and I need to entanglement with another Quantum Computer

I want to process my quantum data in a quantum computer!!

Quantum Internet – Roadmap forward

A Communication Network Exploiting the Quantum Properties of Light



Quantum Computing integrated with the Quantum Internet

Quantum Memory

Quantum Entanglement

Multipoint-to-Multipoint Qubit Transmission

Point-to-Point Qubit Transmission

Quantum Functionality

Cluster Quantum Computing

Blind Quantum Computing in a Quantum Cloud
Quantum Repeaters

Early Field Trials 2021

Ready for Industrial Development QuTech/Others

Quantum Key Distribution (QKD) (**with** end-to-end security)
For Encryption, Authentication, etc. etc.
Other Applications: Password Identification, Position Verification, and more.

Commercial

Quantum Key Distribution (QKD) (**without** end-to-end security)
for Encryption, Authentication, etc. etc.

Quantum Internet – What can it bring?

A Communication Network Exploiting the Quantum Properties of Light

… for two distinct, but similar types of functionality

First, Quantum Key Distribution (QKD) Networks

❖ E2E distribution of Conventional Crypto Keys, via Quantum Key Distribution (QKD)

❖ Limited "Quantum-Distance" thus, Trusted Nodes

❖ Today's Technology

Second, Quantum Information Network (QIN)

❖ E2E distribution of quantum entanglement, for Conventional Crypto keys **AND** Quantum Algorithms on Quantum Computers

❖ Unlimited "Quantum-Distance", via Quantum Repeaters

❖ Very early field trials.

Quantum Networks emerging worldwide

Switzerland, South Korea, China, UK

- Commercial boxes for QKD exist; point-to-point, ~100 km max.
- Multi-hop networks require “trusted nodes”
- Generally seen as insufficiently secure

QKD / QI Networks are taking off soon

Europe

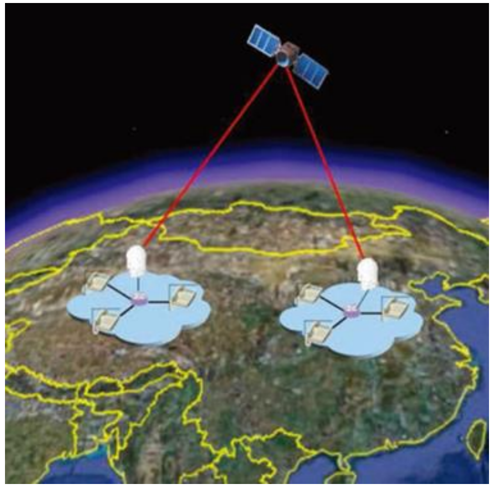
- Quantum Internet Alliance (QIA), and OpenQKD Consortium, building testbed networks
- The Quantum Communication Infrastructure (EuroQCI) Initiative

United States

- Quantum Xchange: 20-mile network, Wall Street to New Jersey
- Chicago area: 30-mile network

China

- QKD via trusted satellite
- 2000 km network using multi-hop ‘trusted nodes’ from Beijing to Shanghai



Beijing
Jinan
Shanghai

Quantum Xchange Launches “Phio” the First Commercial QKD Network for Quantum Communications in the U.S.

Mariya Gabriel
@GabrielMariya

#DA2019eu witnessed the signature of #Malta #Belgium #Germany #Spain #Netherlands #Italy & #Luxembourg of the déclaration to cooperate on building a #Quantum Communication Infrastructure #EuroQCI, boosting EU #cybersecurity & quantum industrial #competitiveness

Quantum Network Applications

Secure a Data Connection Between Two Buildings

Financial

- Distribution of Master Keys
- Securing data to disaster recovery centers
- Secure storage of digital tokens

Governmental

- Encryption between ministries
- Secure document exchange
- Encryption to government data centers

Data Centers and Interconnects

- Encryption to/from cloud storage and computing centers
- Encryption through untrusted interconnects

Critical Infrastructure

- Encryption of data for remote monitoring
- Security on the control and/or management plane

Telecommunications

- QKD as a service
- Security for control and/or management plane
- 5G message authentication
- Data encryption at layer-1

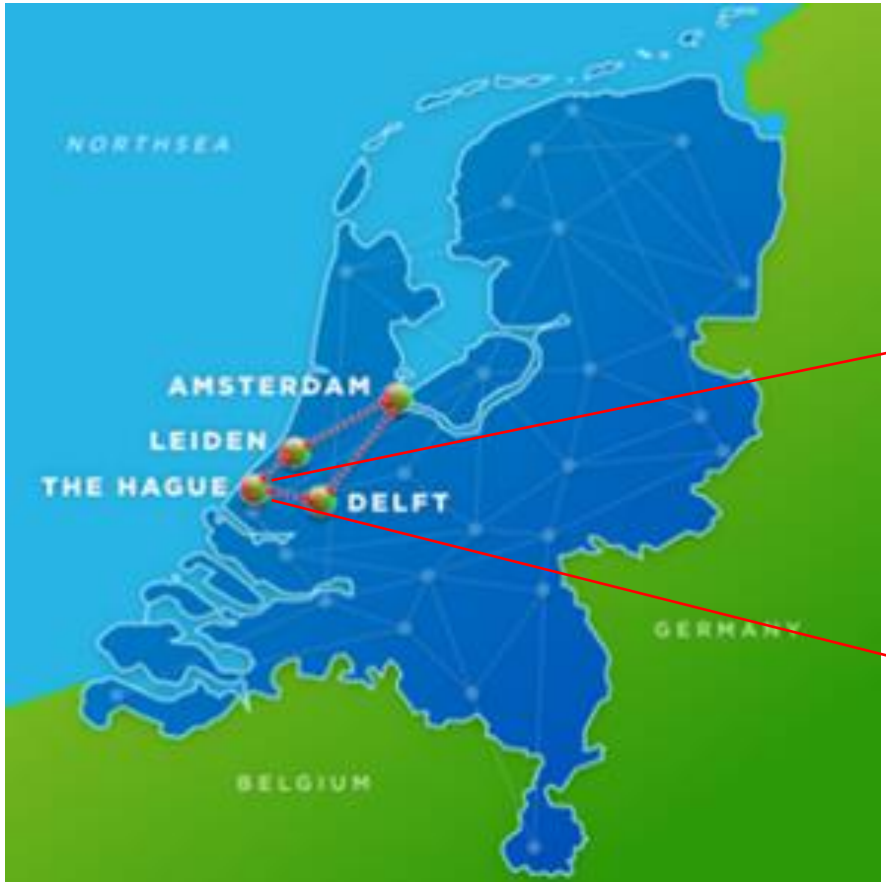
Enterprise Networks

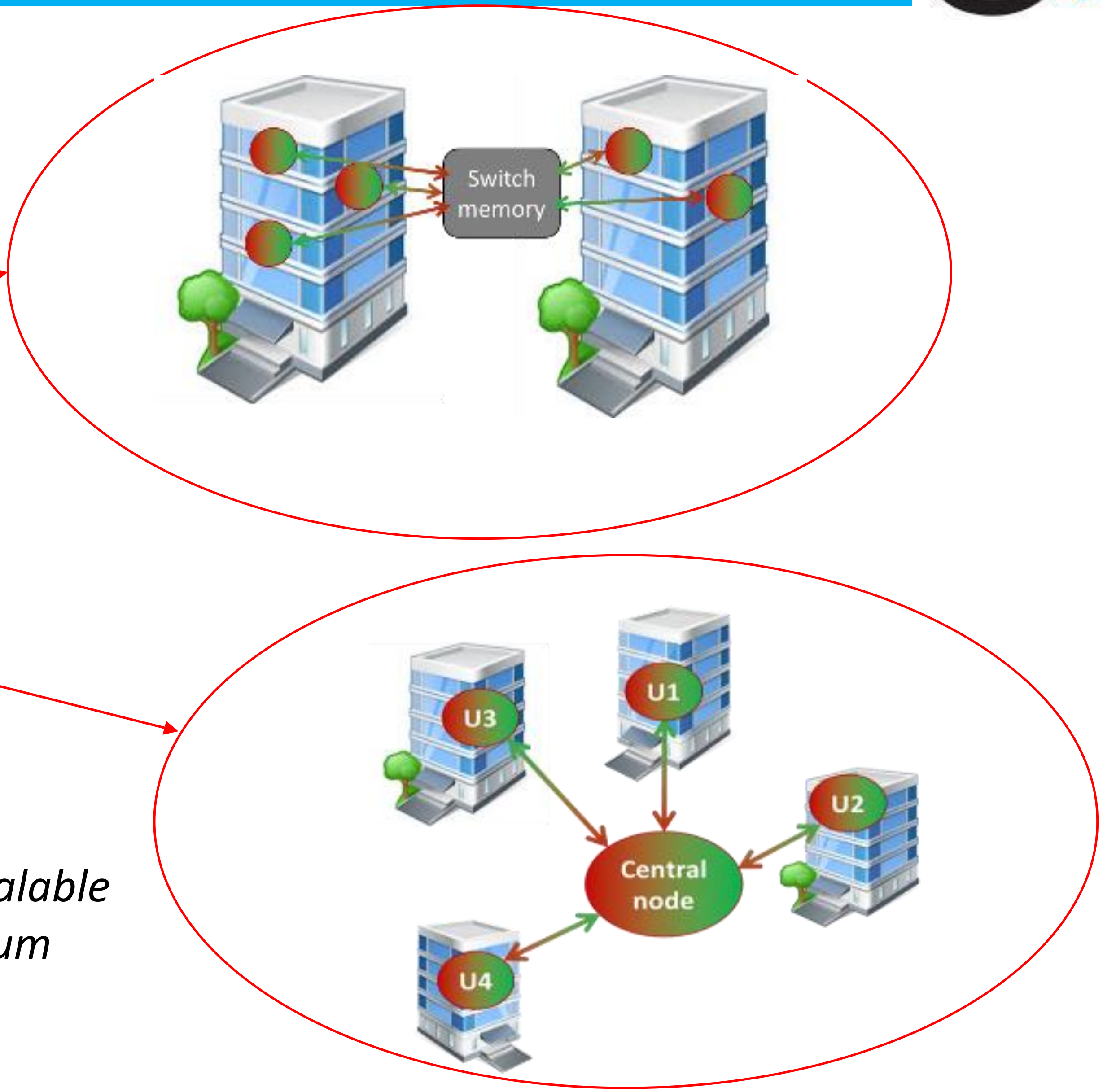
Health Care

Vehicle-to-Everything

Intellectual Property Protection

QuTech - Our Road to Quantum Internet





QuTech is a mission-driven institute that will develop scalable prototypes of a quantum internet… with local quantum processors enabling quantum computation

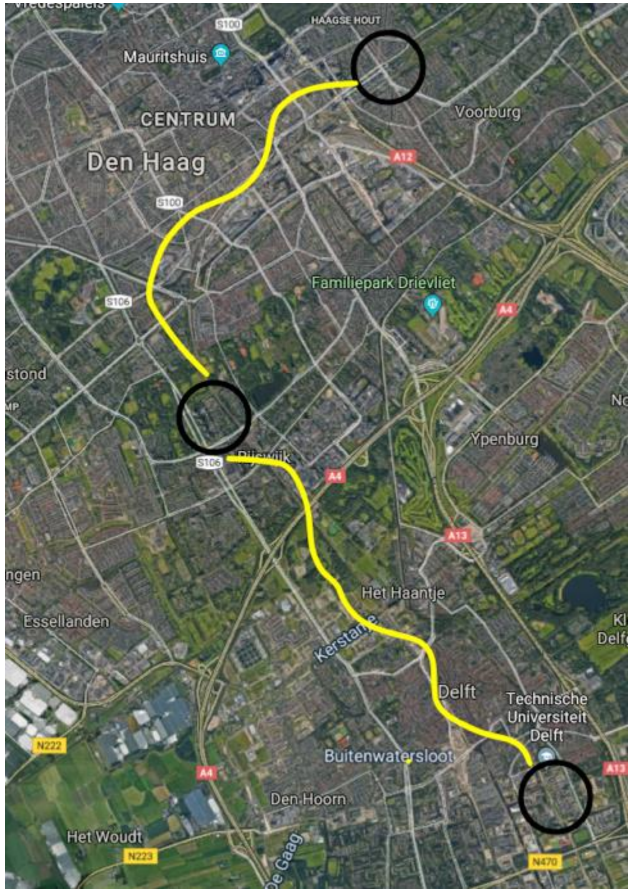
QuTech - Our Road to Quantum Internet

- 2015: First time ever: entanglement experimentally and irrefutable proven
- 2018: First time entanglement “on demand” → towards a true quantum internet!

Nature 526, 682 (2015)
Sci. Rep. 6, 30289 (2016)

QuTech - Our Road to Quantum Internet

December 2020
Inter-City Deployment Begins



2021
End-Points upgraded
to quantum repeater

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1) Introduction – Quantum Internet, QuTech

2) Quantum Key Distribution Boxes – What they look like? What they do?

3) Quantum Key Distribution Networks – What might they look like? What might they do?

4) Quantum Key Distribution Protocols – Why to consider MDI QKD

QKD, in a nutshell

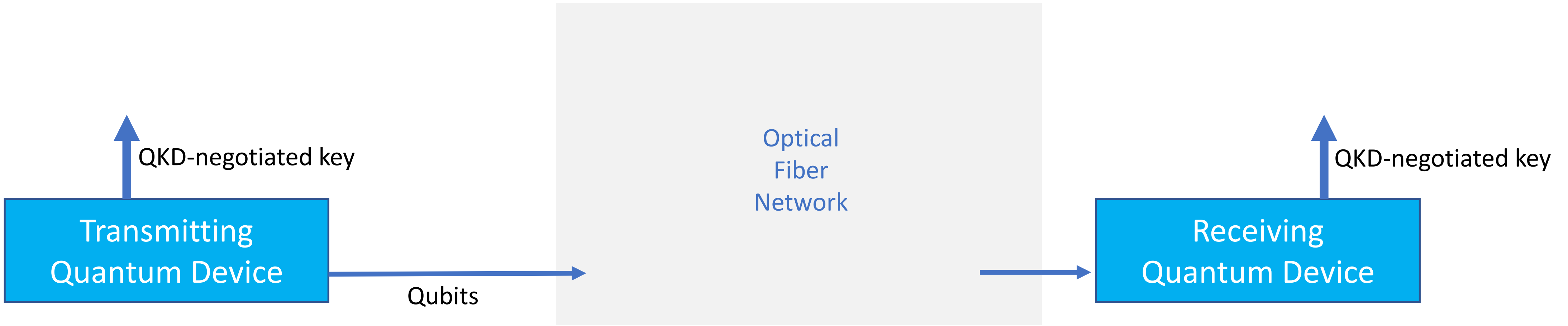
Quantum Key Distribution (in a nutshell):

1. Quantum Devices transmit/receive optical qubits over standard fiber

2. Received Qubits are detected immediately creating ***Quantum Data*** that be used as a ***Cryptographic Key***

3. Any eavesdropping with signals on the fiber is detectable by the QKD devices

4. The ***QKD key can be used by classical symmetric encryptors/decryptors*** to encrypt/decrypt user data

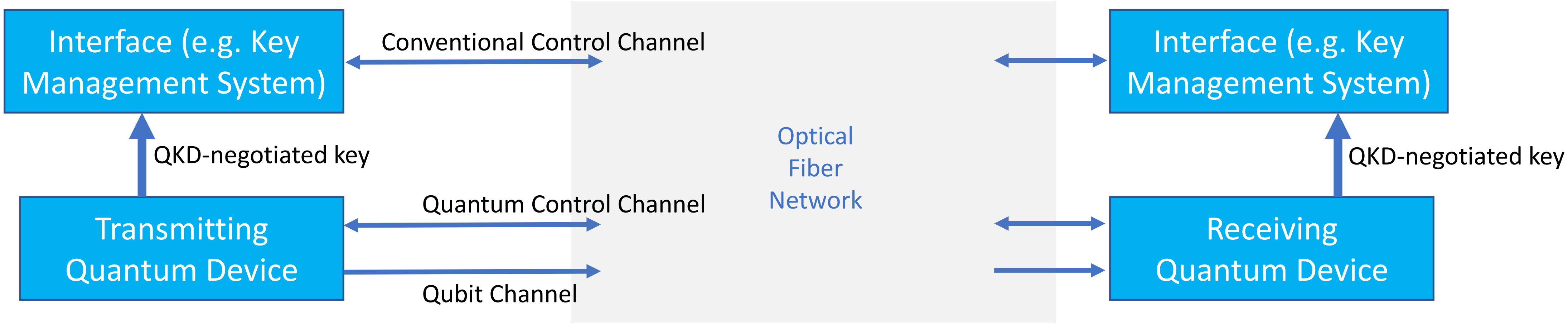


QKD, what's the box do?

1. Qubit Channel performs best on Dark Fiber
   - Operates up to a distance-limit
   - Coexisting WDM/Conventional signals decrease performance/operational distance of QKD

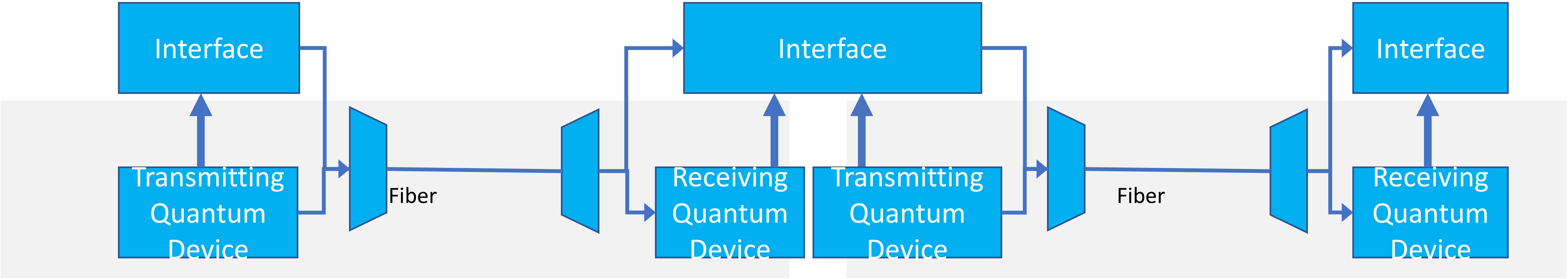
2. Quantum Control Channel for "Quantum-physics" control of certain hardware elements
   - Can be WDM with qubits, decreases performance

3. Conventional Control Channel to enable the network, deliver service request messages, etc.
   - Can be WDM with qubits, decreases performance


Interface (e.g. Key Management System)
Conventional Control Channel
Interface (e.g. Key Management System)
QKD-negotiated key
Optical Fiber Network
QKD-negotiated key
Quantum Control Channel
Transmitting Quantum Device
Receiving Quantum Device
Qubit Channel

QKD, the Trusted Node

The Trusted Node – “Solving” the Distance-Limit



Concerns:

- Key is visible at the Center Node
- One must “Trust” every node along a long path

QKD, A Big Question

What is the Service?

A) Pure Quantum Hardware?

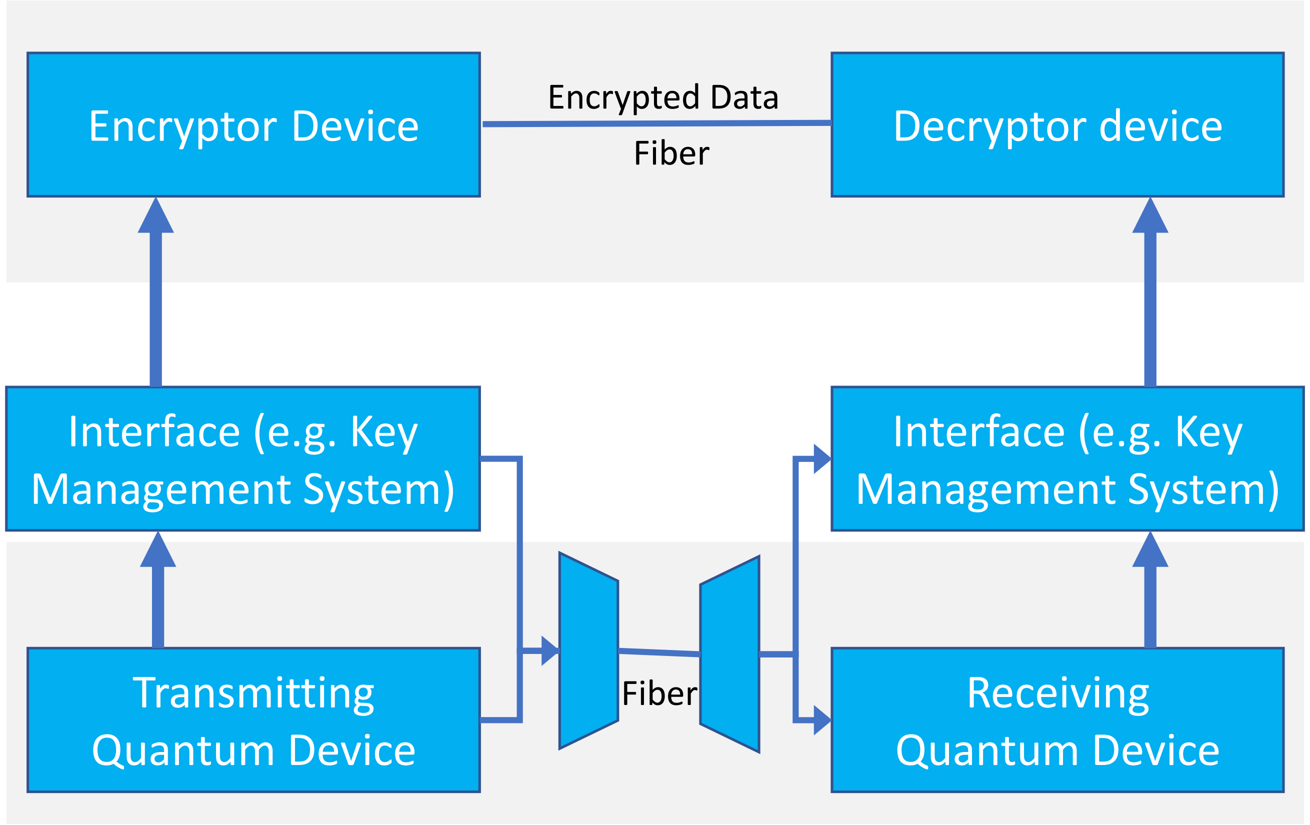
- Supply only Quantum Boxes
- Provide only quantum secret keys, via boxes
- Users responsible for key use, other security hardware/software, fiber, etc.

B) Dedicated Application Hardware?

- Provide Encryption with Quantum Keys?
- Supply Quantum boxes + Encryptors
- Users provide a network for transmission

C) Managed Service (MSP) ?

- Provide a Secure Communication Network
- Create dedicated physical network
- Users simply request service and send input data


Encryptor Device
Encrypted Data
Fiber
Decryptor device
Interface (e.g. Key Management System)
Interface (e.g. Key Management System)
Fiber
Transmitting Quantum Device
Receiving Quantum Device

Some Open Questions

What type of Service to first offer?

- Pure Quantum Hardware? Dedicated Application Hardware? Managed Services?

Quantum Secret Key Rates?

- Depends on the Use Case, what services are requested, and QoS agreements

What does an SLA look like for Quantum?

- Priority? QKD key lengths? Availability? Security parameters?
- Pair-wise defined

Security Level?

- Business confidential? Government Confidential? Government Secret?

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4) **Quantum Key Distribution Protocols – Why to consider MDI QKD**

QKD; There are many Protocols

Many protocols exist:

BB84, BBM92, EB, MDI, CV, SARG, GG02, COW, DPS, etc. etc…

Many ways to compare them:

Near-Term Importance

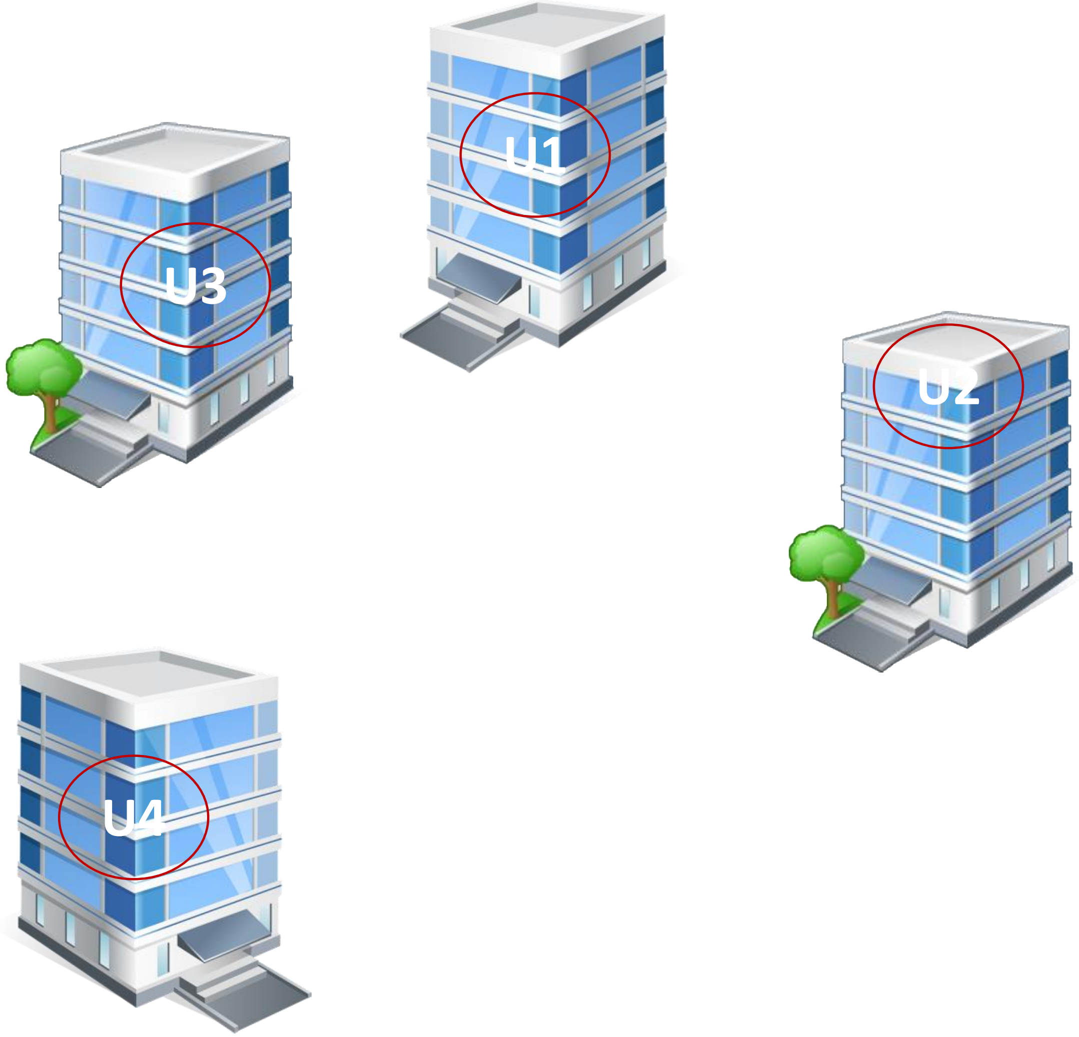
- Technological Readiness Level
- Typical Key Rates
- Maximum Distance
- Security proof of the quantum protocol part
- Implementation Difficulty
- **Point-to-Multipoint**

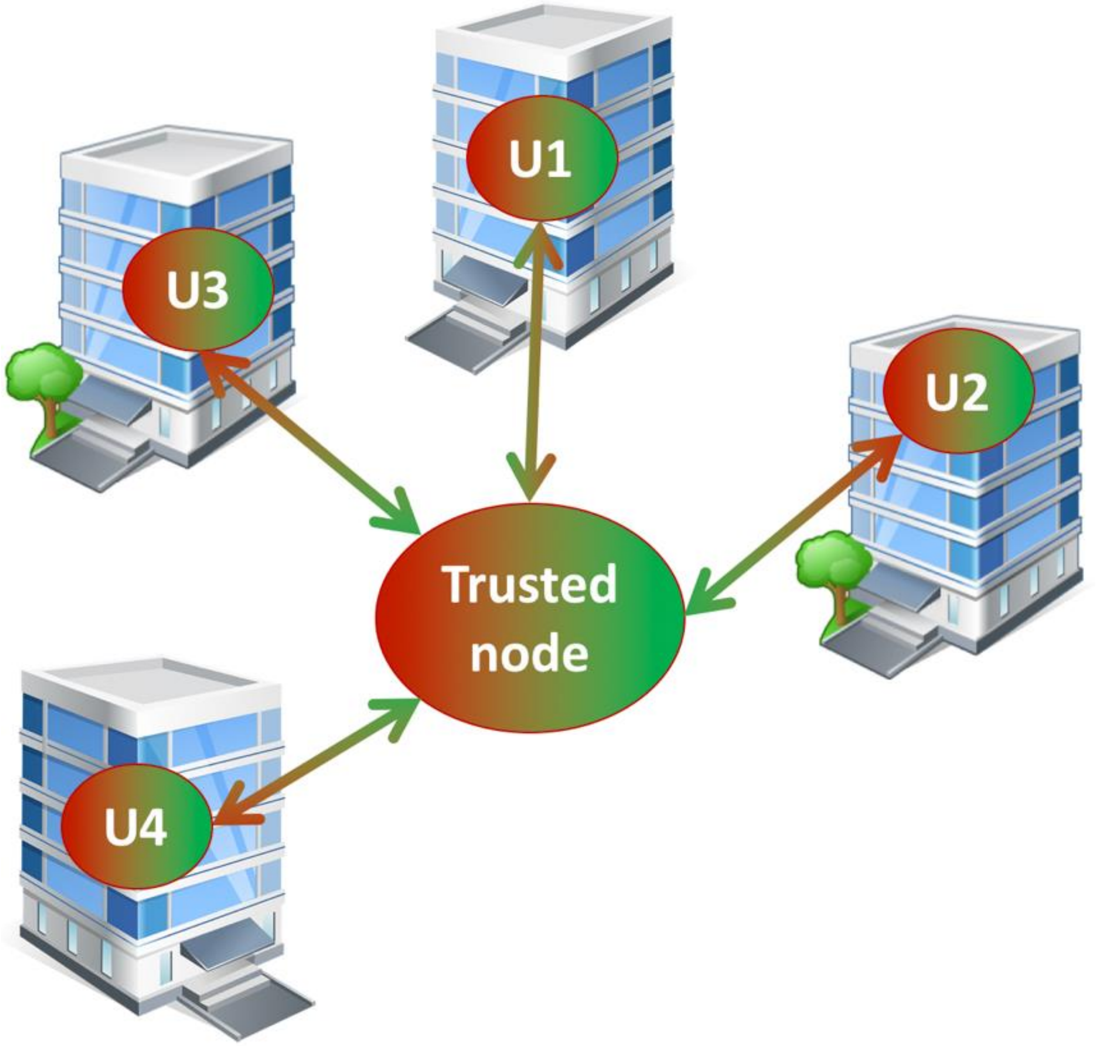
Long-Term Importance

- **Upgradability to QIN**
- **Susceptibility of hardware to attacks**

QKD; There are many Protocols

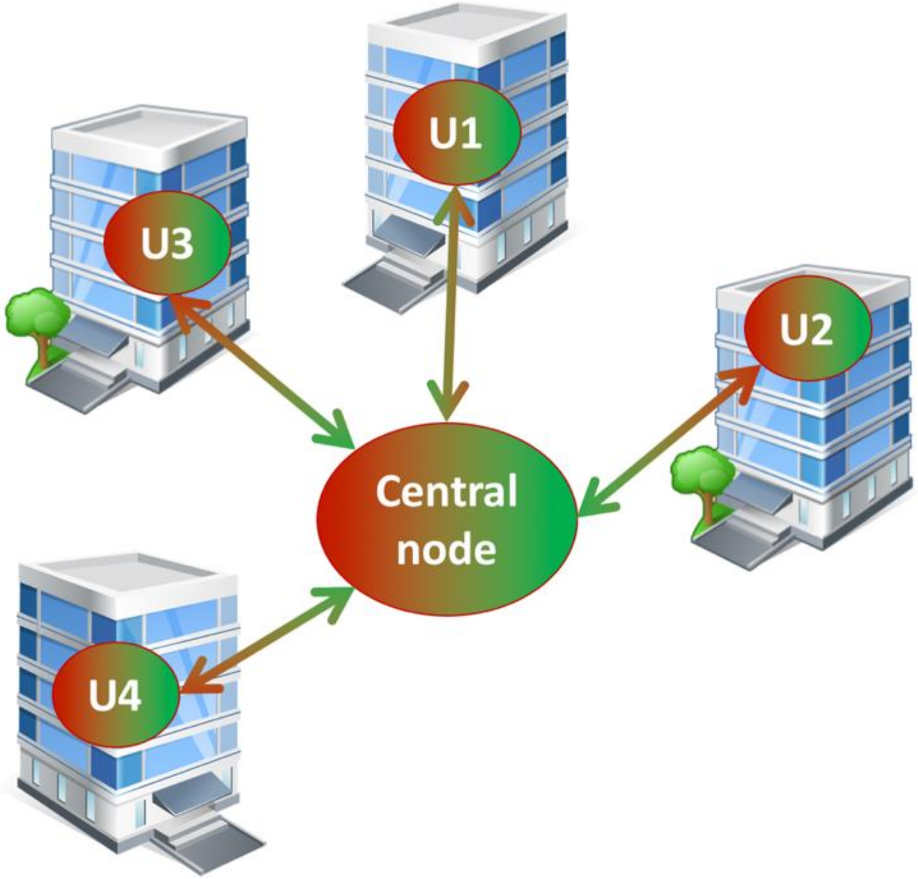
Most QKD Protocols are point-to-point or requires “trusted node”





MDI-QKD

- Measurement-Device-Independent Quantum Key Distribution (MDI-QKD)

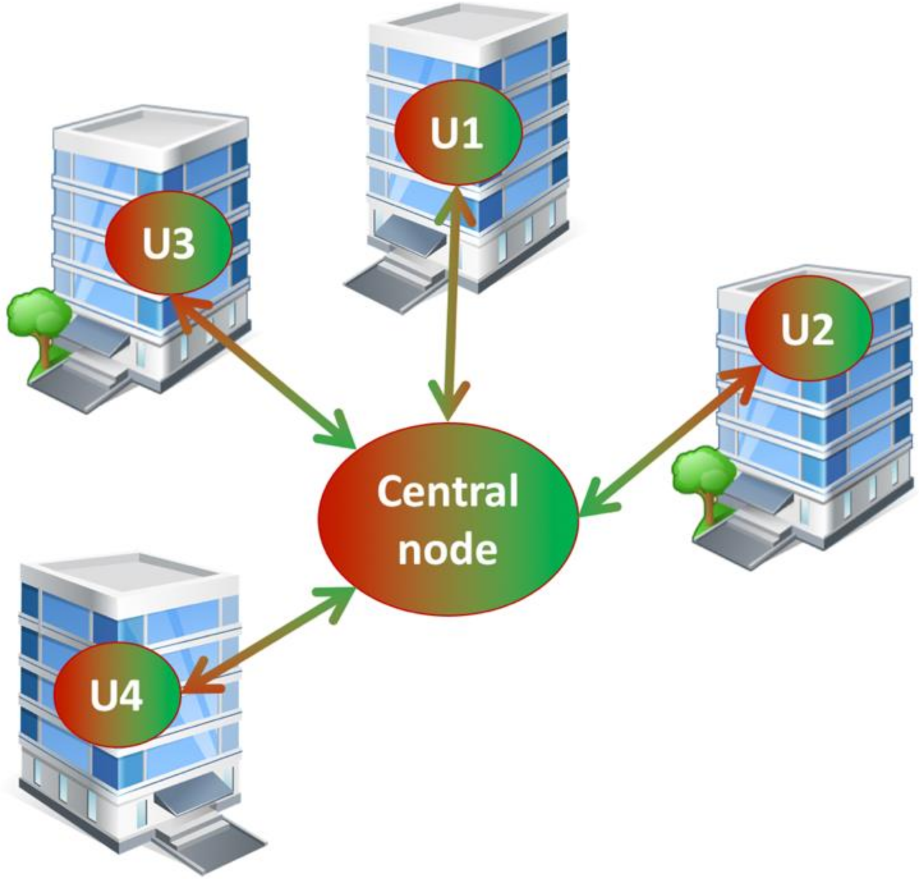


MDI, EB, BBM92: the potential answer to

Point-to-Multipoint
Upgradability to QIN
Susceptibility of hardware to attacks

MDI-QKD

Measurement-Device-Independent (MDI) QKD is Next-Gen QKD



MDI-QKD is more Practical

- MDI-QKD is inherently Networked in a Star network
- Users only need fiber link to Central Node
- Any pair of Users can create secret key

MDI-QKD is more Cost-Effective

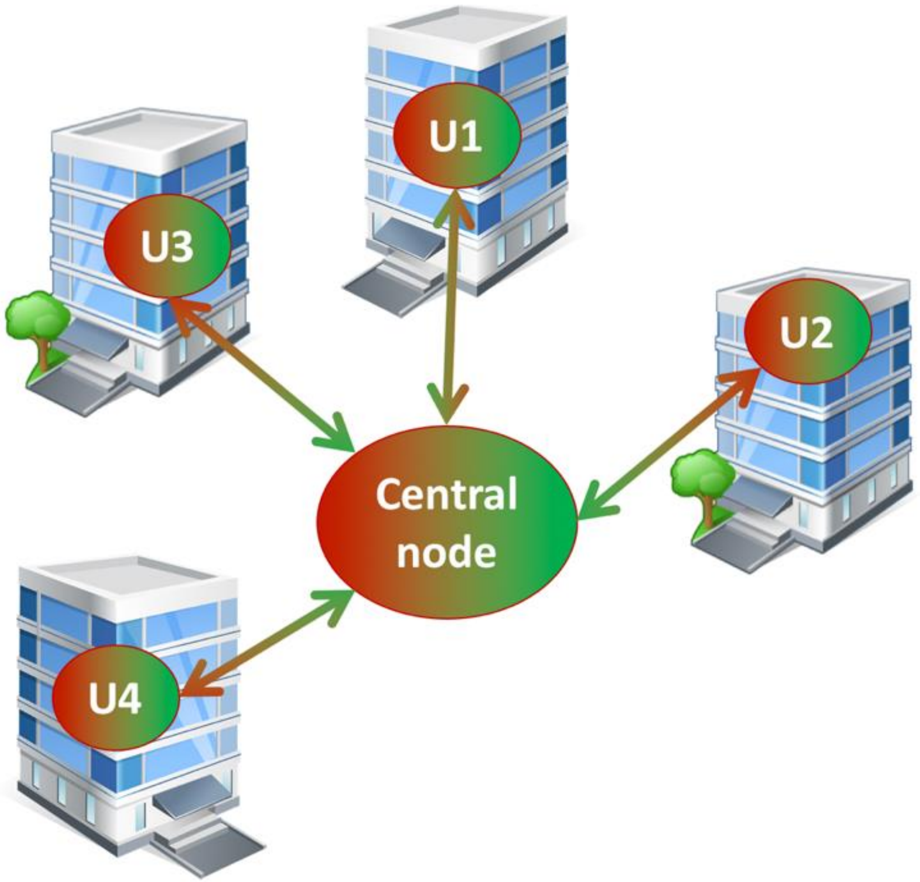
- New Users can be added at anytime with a single connection
- Expensive Hardware is at Central Node
- Same Central Node is needed for Future Quantum Internet → **MDI-QKD network is upgradable for the future**

MDI-QKD is more Secure

- **Central Node is <u>not</u> a trusted node.**
- Central Node attacks physically cannot reveal key, nor reveal sensitive information. Best attack is a DoS.
- End-Points are send-only and not vulnerable to receiver attacks

MDI-QKD – Better Security

Measurement-Device-Independent (MDI) QKD is Next-Gen QKD



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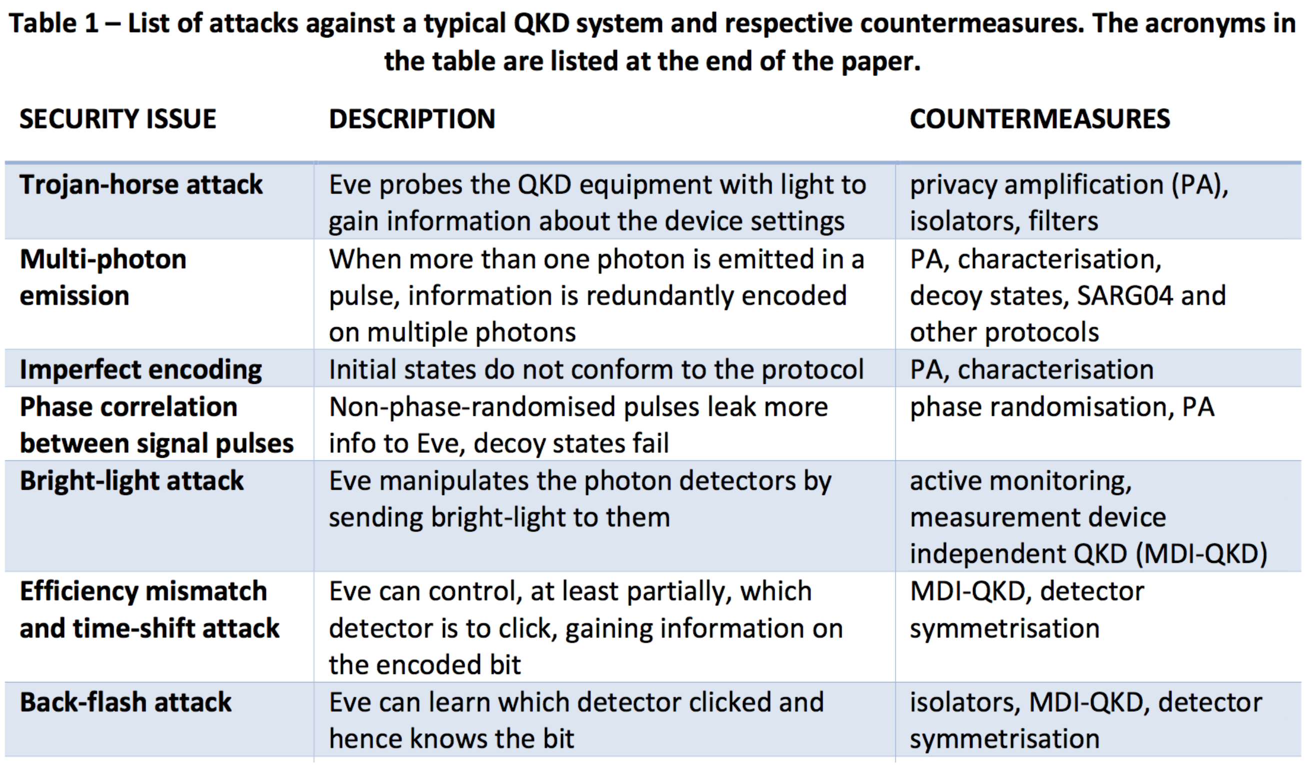


Table 1 – List of attacks against a typical QKD system and respective countermeasures. The acronyms in the table are listed at the end of the paper.

SECURITY ISSUE	DESCRIPTION	COUNTERMEASURES
Trojan-horse attack	Eve probes the QKD equipment with light to gain information about the device settings	privacy amplification (PA), isolators, filters
Multi-photon emission	When more than one photon is emitted in a pulse, information is redundantly encoded on multiple photons	PA, characterisation, decoy states, SARG04 and other protocols
Imperfect encoding	Initial states do not conform to the protocol	PA, characterisation
Phase correlation between signal pulses	Non-phase-randomised pulses leak more info to Eve, decoy states fail	phase randomisation, PA
Bright-light attack	Eve manipulates the photon detectors by sending bright-light to them	active monitoring, measurement device independent QKD (MDI-QKD)
Efficiency mismatch and time-shift attack	Eve can control, at least partially, which detector is to click, gaining information on the encoded bit	MDI-QKD, detector symmetrisation
Back-flash attack	Eve can learn which detector clicked and hence knows the bit	isolators, MDI-QKD, detector symmetrisation

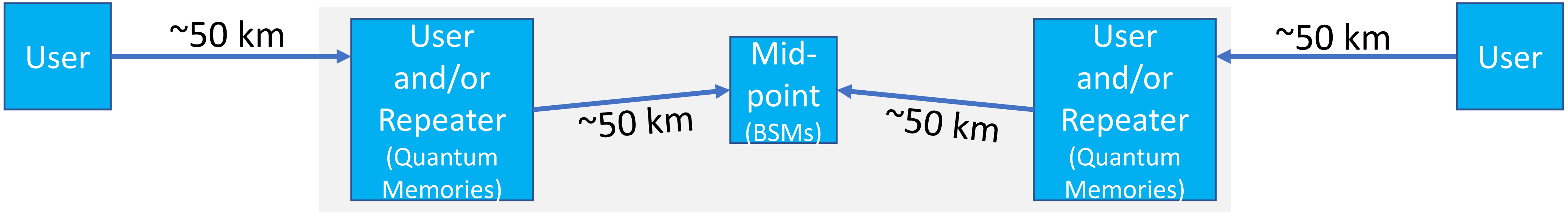
ETSI White Paper No. 27, July 2018, "Implementation Security of Quantum Cryptography"

MDI-QKD - Upgradability

Measurement-Device-Independent (MDI) QKD is Next-Gen QKD

Upgradability to QIN

- QIN does Entanglement generation, swapping, teleportation
- Quantum Repeaters not available yet, BUT
  - They require Mid-Point stations,
    identical to MDI Central Node!


User
~50 km
User and/or Repeater (Quantum Memories)
~50 km
Mid-point (BSMs)
~50 km
User and/or Repeater (Quantum Memories)
~50 km
User

Physical Network Building: Consider the end Goal: QIN

- Midpoint stations needed
- Asymmetric links degrades performance quickly…

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Quantum Internet – Top 7 Facts!!

1) **Quantum Internet will use quantum-technology to provide quantum-services to Users.**

2) **Quantum will not replace conventional networks; only supplement with new functionality**

3) **Communication channels will be Optical (fiber, free-space, satellites, etc.)**

4) **Fibers will be used for Quantum Internet**
   - Low enough loss for Quantum (<30 dB), with no conventional active elements

5) **Quantum Boxes can be made 19" rack compatible**
   - QuTech and others do it

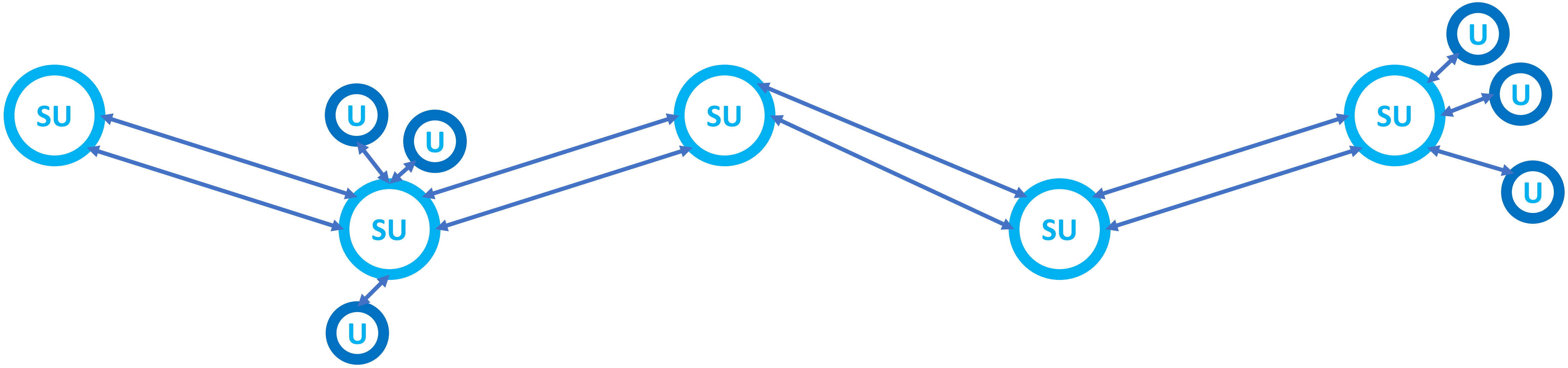
6) **Infrastructure locations will be responsible for support, and own security**
   - Energy, cooling, access controls, logging, etc. etc.
   - Specialized dry-cryo cooling? Compressed gasses?

7) **Redundancy can be built into the network**
   - Though, best techniques haven't been explored

8) **There is a lot of uncertainty still**
   - Who's going to build hardware? Where do we lay down? How much will governments control? Who's going to invest? How do we get to QIN?

The High-Level Network View – 2 Years

Metro-Scale Chains?



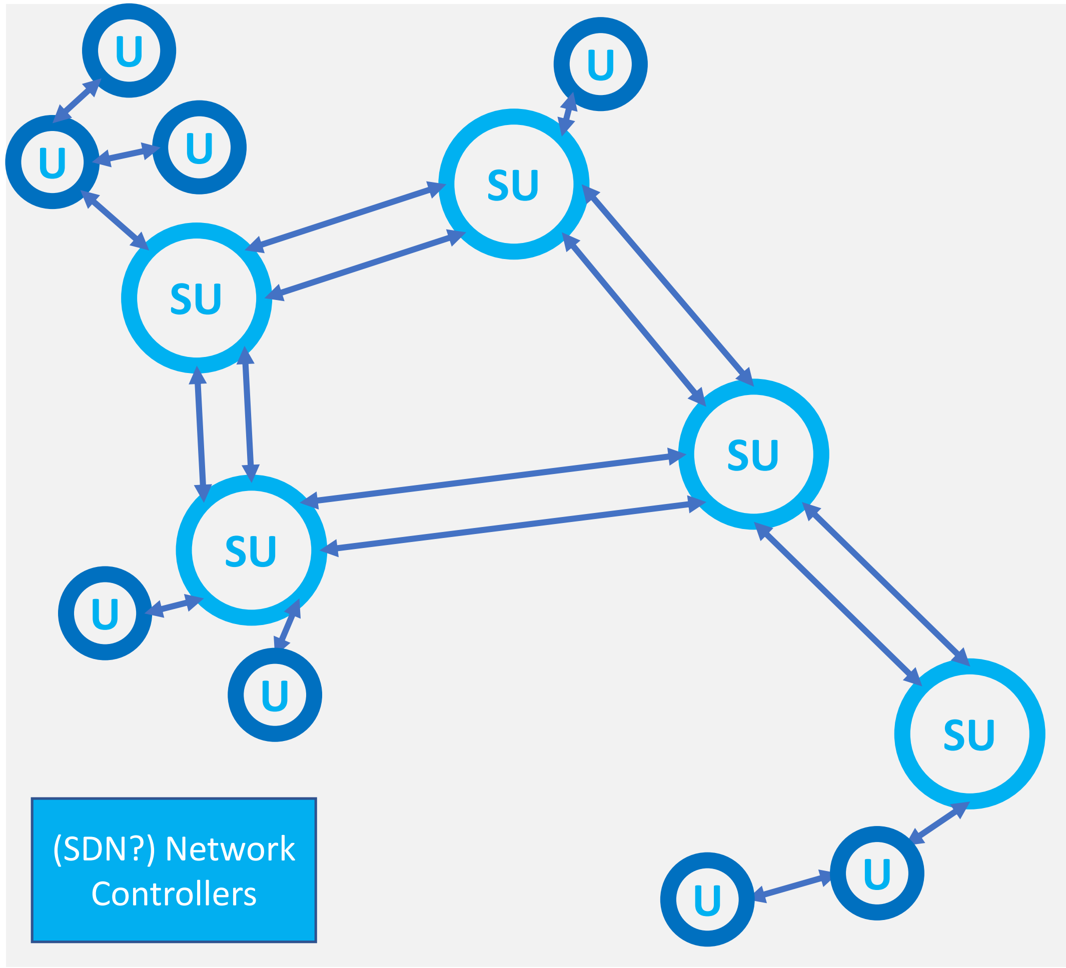
- Metropolitan-Scale Chains
- A few per continent likely
- Focus on developing know-how with Operational Deployment

Composed of:

- High-Bandwidth Super-Users
- Super-Users Acting as Trusted Nodes
- Nearby Users (low-bandwidth or non-quantum) accessing a “backbone”

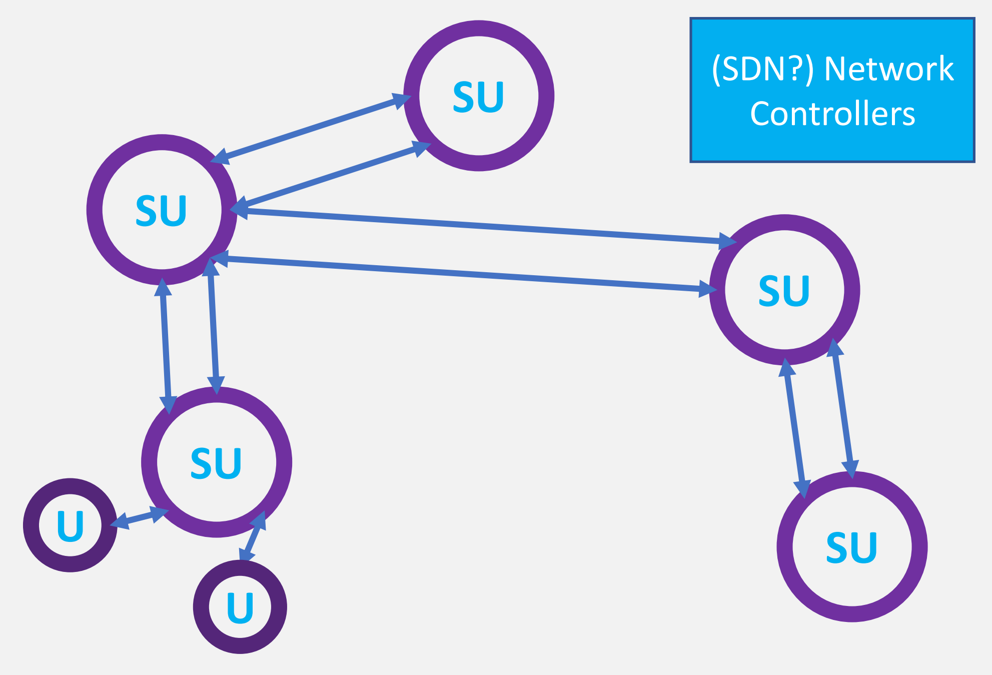
The High-Level Network View – 5 Years

A Metro-Network



- Metropolitan-Scale Networks, few per continent
- Still developing Operational Deployment
- Further professionalization of hardware, of service, of network designs/management

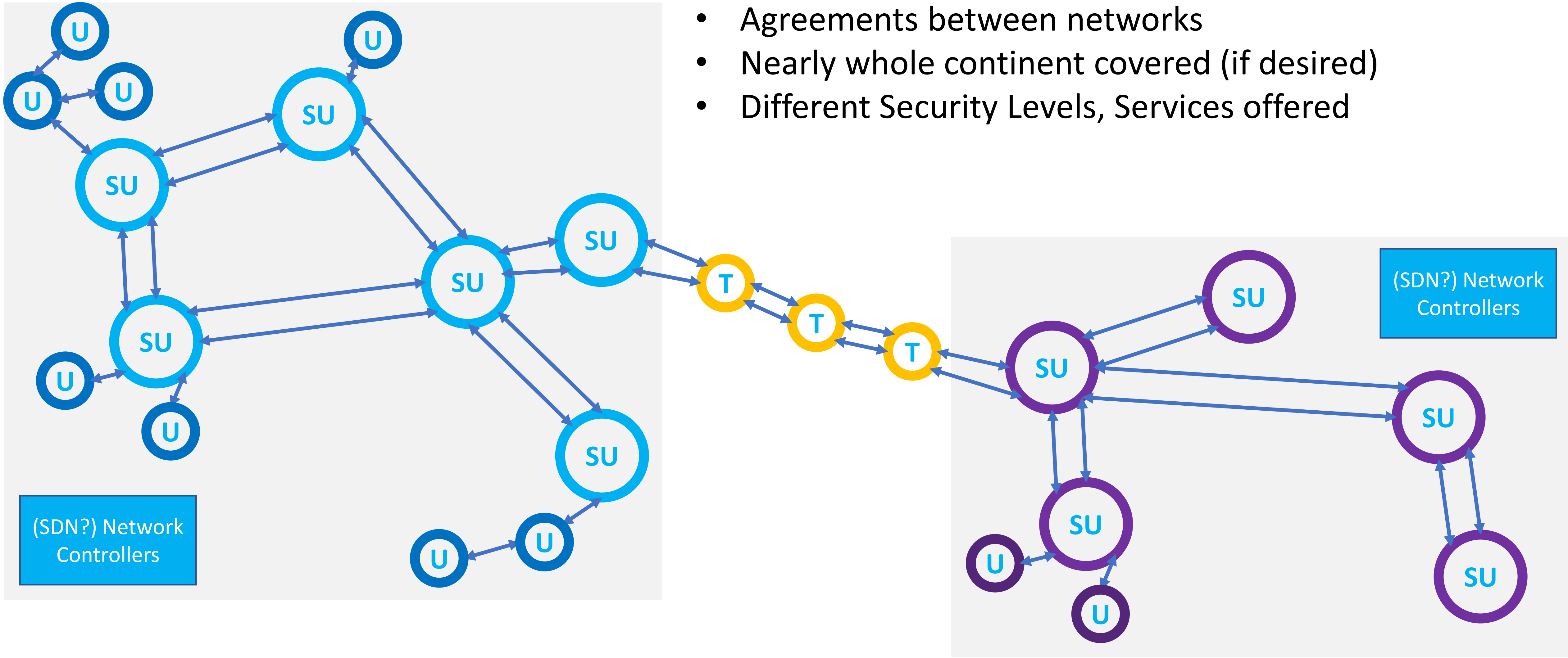
And then more Metro-Networks



The High-Level Network View – 10 Years

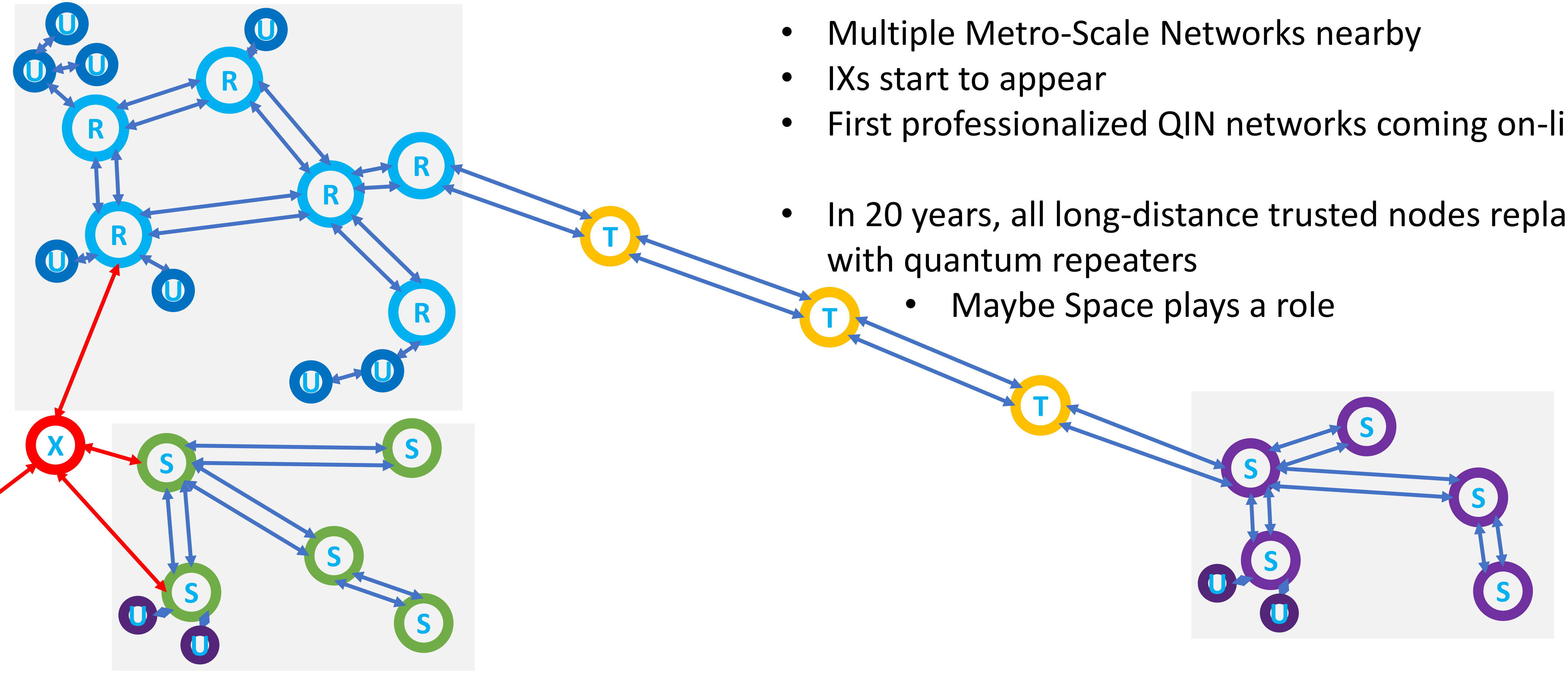
Connected Metro-Networks

- Long-distance backbone of Trusted nodes
- Agreements between networks
- Nearly whole continent covered (if desired)
- Different Security Levels, Services offered



The High-Level Network View – 15 Years

Close, but Separate Networks, and slowly QIN



- Multiple Metro-Scale Networks nearby
- IXs start to appear
- First professionalized QIN networks coming on-line

- In 20 years, all long-distance trusted nodes replaced with quantum repeaters
  - Maybe Space plays a role

Some Open Questions

WDM Multiplexing or Dark Fiber?

- Optimize fiber-use or optimize Quantum performance?

Is Point-to-Point sufficient medium term? Or Point-to-Multipoint needed sooner?

Are Trusted Nodes allowed?

- Certainly required in some situations…
- Users & Governments likely to decide. Protection measures needed.

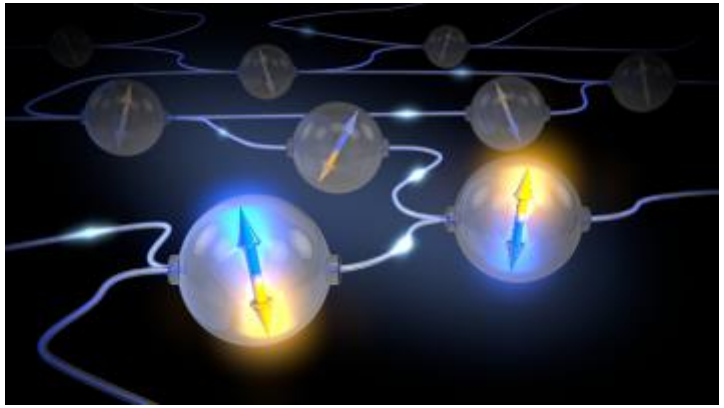
Enrollment into the quantum network?

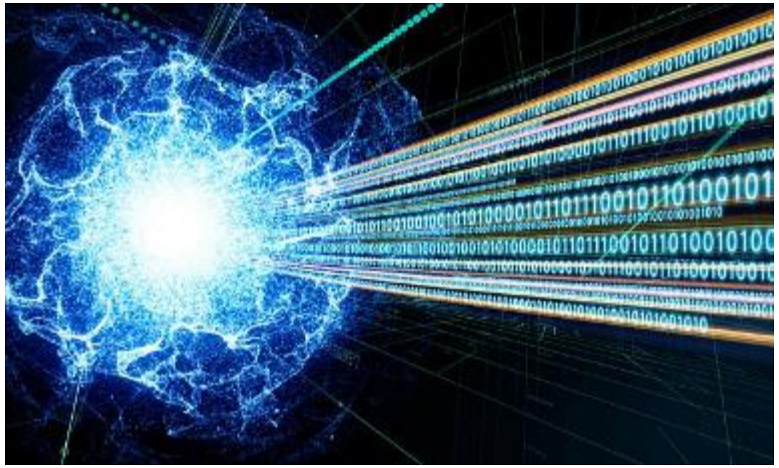
- We want to avoid vendor-lock in
- Can anyone connect to Exchanges?
- Usage by suspicious actors?

Lawful Interception?

Take aways

- Quantum Key Distribution for now, and Full Quantum Internet will come later
- QuTech's Dutch Network starts up next month, upgrading to early repeaters next year
- Open Questions in Service to Offer, WDMs, Trusted Nodes, and Network Management
- Many QKD protocols exist, each with benefits and drawbacks
  - MDI-QKD for better security, upgradability, cost-scaling
- We should design the physical topology correctly now, so QIN can come easily later.





Wehner et al, Science 362, 6412 (2018).
YouTube: "Joshua Slater QCrypt"

Thank you!